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Møller, Henrik

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H. Moller
Aalborg University
Aalborg, Denmark

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CANCELLATION OF CROSSTALK IN ARTIFICIAL HEAD RECORDINGS REPRODUCED THROUGH LOUDSPEAKERS

Henrik Møller
Institute of Electronic Systems
Aalborg University
Fredrik Bajers Vej 7
DK-9220 Aalborg Ø, Denmark

1. INTRODUCTION

The basic concept of the artificial head recording technique is well-known. In any listening situation the input to the hearing mechanism consists of two one-dimensional signals, e.g. the sound pressure at the two eardrums. If a set of recording/playback equipment is able to create the same sound pressure at the eardrums of a listener as would have been in the concert hall, then the acoustic experience is reproduced correctly, including directional aspects, reflections, reverberation etc.

In practice, recordings are made with microphones in the ear canals of a carefully designed model of a human head, including pinnae. Reproduction is carried out through headphones, which ensures that each channel is only reproduced in one ear.

2. REPRODUCTION THROUGH LOUDSPEAKERS

The good directional characteristics of an artificial head recording are destroyed if it is reproduced through loudspeakers. This is due to the crosstalk which is introduced in any free field listening. Crosstalk means that the right speaker is heard not only with the right ear but also with the left ear and vice versa.

However, it can be shown that it is possible to add an artificial crosstalk which cancels out the natural crosstalk. This principle is shown in the following.

X_{left} and X_{right} denote the two channels which are to be reproduced as sound pressure at the eardrums. Y_{left} and Y_{right} are the signals presented to the loudspeaker terminals. Z_{left} and Z_{right} denote the sound pressure at the two eardrums. X and Y have the unit V, while the unit of Z is Pa. The transfer functions from Y to Z are denoted with H as indicated in Figure 1. H has the unit Pa/V.

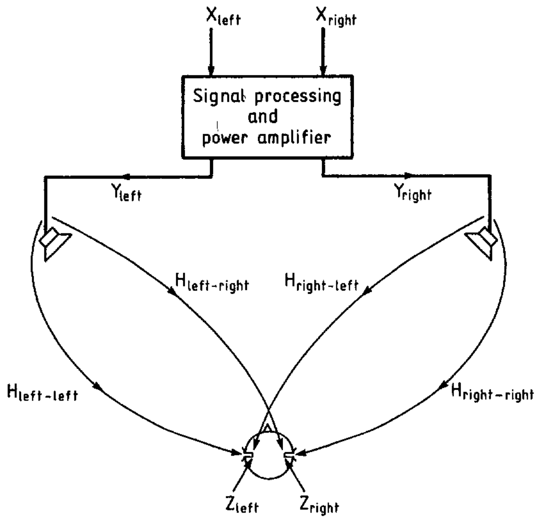


Figure 1. Principal diagram showing the transmission from recording to sound pressure at the eardrums.

Now we have

$$Z_{left} = H_{left-left} \cdot Y_{left} + H_{right-left} \cdot Y_{right} \tag{1}$$

$$Z_{right} = H_{left-right} \cdot Y_{left} + H_{right-right} \cdot Y_{right} \tag{2}$$

What we want, is that

$$Z_{left} = k \cdot X_{left} \tag{3}$$

$$Z_{right} = k \cdot X_{right} \tag{4}$$

k being constant of unit Pa/V. If we combine (1) with (3), (2) with (4), and solve with respect to Y, we get

$$Y_{left} = k \cdot (H_{right-right} \cdot X_{left} - H_{right-left} \cdot X_{right})/D \tag{5}$$

$$Y_{right} = k \cdot (H_{left-left} \cdot X_{right} - H_{left-right} \cdot X_{left})/D \tag{6}$$

$$D = H_{left-left} \cdot H_{right-right} - H_{left-right} \cdot H_{right-left} \tag{7}$$

Some further manipulation is appropriate.

The loudspeaker frequency response is isolated through introduction of P, the sound pressure at the centre of the head, but with no head present. Then

$$H_{left-left} = \left.\frac{Z_{left}}{Y_{left}}\right|_{Y_{right=0}} = \left.\frac{Z_{left}}{P}\right|_{Y_{right=0}} \left.\frac{P}{Y_{left}}\right|_{Y_{right=0}} \tag{8}$$

$$\left.\frac{Z_{left}}{P}\right|_{Y_{right=0}} = FFC_{left-left} \tag{9}$$

could be denoted Free-Field-Correction of the head for a sound originating from the left loudspeaker and reaching the left ear. The unit in Pa/Pa.

$$\left.\frac{P}{Y_{left}}\right|_{Y_{right=0}} = LFFR_{left} \tag{10}$$

is the Loudspeaker Free-Field-Response for the left loudspeaker. The unit is Pa/V. Now (8) can be written as (11) and similar expressions can be found for the other H as given in (12), (13) and (14).

$$H_{left-left} = FFC_{left-left} \cdot LFFR_{left} \tag{11}$$

$$H_{left-right} = FFC_{left-right} \cdot LFFR_{left} \tag{12}$$

$$H_{right-left} = FFC_{right-left} \cdot LFFR_{right} \tag{13}$$

$$H_{right-right} = FFC_{right-right} \cdot LFFR_{right} \tag{14}$$

If symmetri is assumed, then

$$LFFR_{left} = LFFR_{right} = C \tag{15}$$

$$FFC_{left-left} = FFC_{right-right} = A \tag{16}$$

$$FFC_{left-right} = FFC_{right-left} = B \tag{17}$$

(5) and (6) can now be rewritten

$$Y_{left} = \frac{A}{A^2 - B^2} \cdot (X_{left} - X_{right} \cdot \frac{B}{A}) \cdot \frac{k}{C} \tag{18}$$

$$Y_{right} = \frac{A}{A^2 - B^2} \cdot (X_{right} - X_{left} \cdot \frac{B}{A}) \cdot \frac{k}{C} \tag{19}$$

This signal processing is shown in block diagram form in Figure 2.

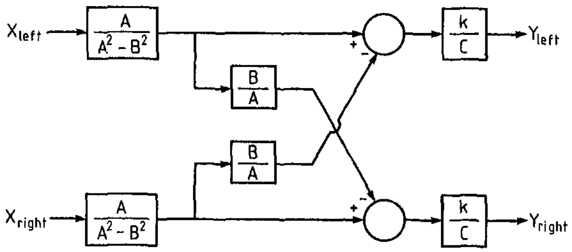


Figure 2. The signal processing of equations (18) and (19) shown in block diagram form.

The blocks to the right perform a gain control and an equalization of the loudspeakers. The left blocks are similarly introduced in the direct signal path of both channels and thus also perform an equalization. Among other things this compensates for the fact, that the ear canal appears two times in the transmission path: once at the recording and once at playback.

The real suppression of the crosstalk is carried out by the crosscoupling of the two centre blocks.

3. REALIZATION

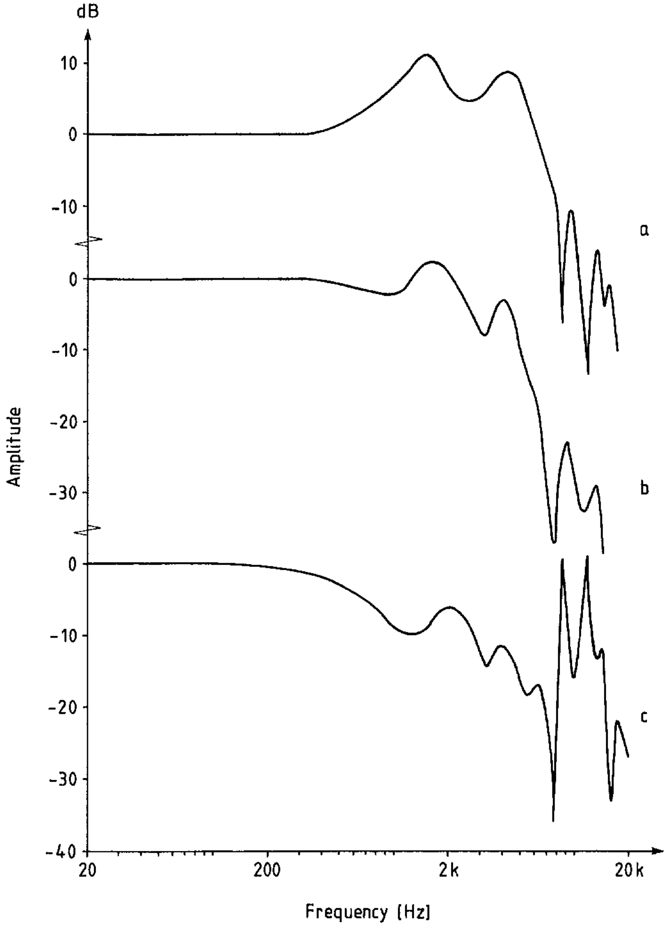
The above given functions were measured on a Neumann Type KU80 i artificial head, see Figure 3.

Until now the effort has been concentrated on realization of the crosscoupling B/A as shown in Figur 3c. A possible way will be to approximate B/A with an analogue filter or a recursive digital filter. However, as accuracy is expected to be essential, it has been realized as a Finite Impulse Response filter using Motorola XSP 56200 processors. The impulse response of the filter, calculated as the inverse Fourier transform of B/A is shown in Figure 4. At the time of printing, the blocks k/C and $A/(A^2 - B^2)$ have not been realized.

4. ASSESSMENT

The suppression of crosstalk is very effectively demonstrated in an anechoic room. With pink noise applied to both channels, the listener perceives the sound as being located in the head, like when listening with headphones. When the noise is applied to only one channel, the listener gets the impression of listening to a sound source located immediately outside the appropriate ear. If this ear is closed with a finger or an earplug, the listener is able to clearly indicate the correct position of the head by searching for minimum sound level at the opposite ear.

At present the reproduction of processed artificial head recordings have only been subjectively evaluated. In general, listeners agree that the directional reproduction is at least as good as with headphones. Many listeners even indicate a better spatial discrimination, especially in



Figur 3. Magnitude of transfer functions:
a) A (Free Field Correction for the ear for sound coming from the same side as the ear),
b) B (Free Field Correction for the ear for sound coming from the opposite side),
c) B/A
All curves are given for sound in the horizontal plane, 45^0 off-frontal incidence.

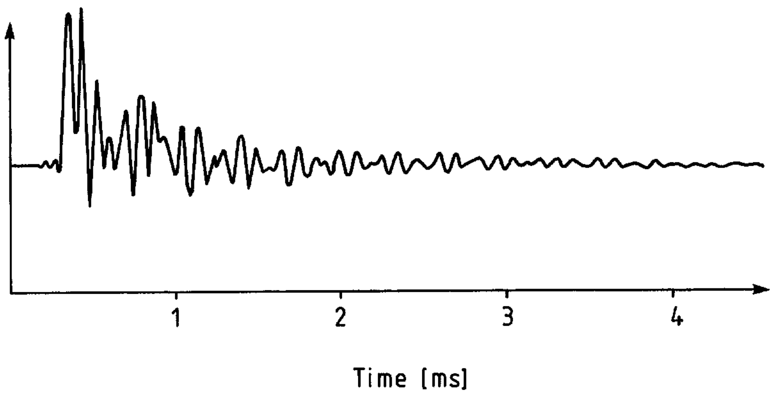


Figure 4. Impulse response of B/A.

the front region. The effect of the system is unexpectedly independent of head position, when only the distances to the two speakers are kept equal.

5. FUTURE WORK

Further investigations have been planned on the following matters:

a) Quantitative and objective evaluation of the observations given above in Section 4.

b) Evaluation of the significance of the blocks $A(A^2 - B^2)$ and k/C.

c) Significance of impulse duration in the realization of filters.

d) The possibility of realizing the blocks of Figure 2, using recursive Infinite Impulse Response filters.

e) The possibility of using a normal listening room. The system is not formally limited to anechoic rooms, but for normal living rooms much longer impulse responses occur, and more computing power is needed.

f) The construction of the artificial head. Figure 5 shows a principal diagram of the signal path from the sound field without a listener present to the sound pressure at the eardrum. It can be argued that full directional information is present in the open circuit Thevenin sound pressure at the entrance to the ear canal. If this pressure is recorded rather than the pressure at the eardrum, all transfer functions are more regular, and the blocks of Figure 2 become easier to realize. Furthermore, the final reproduction is less influenced by differences between the artificial ear and the ear of the listener, since a smaller part of the artificial ear is used. Recording with Neumann Type KU81 i artificial head is expected to approach this situation.

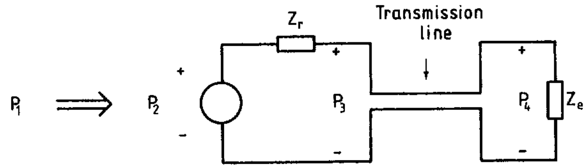


Figure 5. Principal diagram of the signal path from the sound field without a listener present to the sound pressure at one eardrum. P_1 denotes the pressure without a listener, P_2 the open circuit Thevenin pressure at the entrance to the ear canal, P_3 the actual pressure at the entrance to the ear canal, and P_4 the pressure at the eardrum. Z_r is the radiation impedance seen from the ear canal, and Z_e is the impedance of the eardrum. The ear canal is represented by a transmission line. Only the transmission from P_1 to P_2 is dependent on the angle of incidence and the distance of the sound source. Thus, it can be argued that P_2 contains full spatial information.

g) Problems at frequencies where A and B are approximately equal, and thus D is close to zero. This happens especially at low frequencies.

6. ACKNOWLEDGEMENTS

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